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CONTROLLED IMAGE DESIGN:
The management of stereophonic image quality

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Summary

Historically, the basis for the acoustic design of control rooms for stereophony has been the reduction of discrete reflections by means of sound absorption. As an alternative, the use of non-absorbent surfaces to direct early reflections away from the listener makes it possible to obtain good stereo image sharpness without making a 'dead' acoustic environment. It also makes the stereophonic effect less dependent on the room. To test the principle, an experimental room was constructed. This contained a region around the main listening position from which early reflected sound was excluded.

Following successful evaluation of the experimental installation, the principle was used in the BBC as the basis for the design of three refurbished control rooms in Broadcasting House, London and one new control room for the Transcription Service in Bush House. The results of acoustic tests from these areas are presented. The problems of reflections from the top surfaces of mixing desks are also discussed.

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1. INTRODUCTION

This Report is concerned with some of the aspects of room acoustic design that relate to the human perception of the stereophonic illusion, especially in studio control rooms.

The control room (and its associated equipment) is the primary means of evaluating the quality of reproduced sound. However, it is the one part of the programme chain which is most difficult to design and control. The magnitudes of the defects introduced by the loudspeakers and the room acoustics exceed the imperfections of the purely electronic equipment by large factors. Nevertheless, the control room is the only means of evaluating the aesthetic and technical sound quality of a performance or a programme — as it may be heard by the audience.

2. HISTORICAL BACKGROUND

In the earliest days of separate rooms, in which any kind of quality monitoring was intended, the principle aim of the acoustic design was to create some representation of the eventual listener's environment. Indeed, studies were carried out into domestic living-room conditions in order to obtain numerical values for reverberation time. [1, 2] These results have never been fully incorporated into the design of BBC control rooms. However, in the past, there was a token element from those results, with design mid-band reverberation times of about 0.3 s. Technical considerations about the need for a more 'analytic' acoustic — for programme production rather than for recreational listening — ensured that such a control room design target was significantly lower than the values measured for actual domestic rooms (0.4 – 0.8 s). Materials with specially high acoustic absorption characteristics were used to reduce the reverberation time from the high values that would otherwise occur naturally. The acoustic design was limited to the control of the overall reverberation and acoustic anomalies such as 'flutter echoes'.

That principle survived essentially intact until the advent of stereophonic sound. Then, with the emphasis on objectively accurate image localisation, the disturbing effects of individual reflections of sound energy from surfaces and objects within the room became apparent.

Strong, discrete reflections closely following the arrival of the direct sound at the listener's position can cause distortion of the perceived sound stage. Beginning in the early 1960s, acoustic treatment was installed selectively, to control these reflections by absorption. This led to an acoustic design in which patches of absorption, particularly for high frequencies, were strategically placed around the room and especially around the loudspeakers (which were almost always free-standing). To maintain (as much as possible) the diffuse sound field which was felt to be essential, the remainder of the room was usually treated to about the same extent.

Unfortunately, comprehensive control of reflections in this way leads to the installation of large quantities of acoustic treatment and acoustically 'dead' rooms. Over a period of about 10 years, from 1982 nearly to the present (1994), the extent of this treatment has progressively increased. Measured 'reverberation times' of less than 0.15 s have frequently been encountered. This large amount of acoustic treatment is expensive in terms of both capital and installation costs and of space within the the room. It leads to rooms which are oppressive for the occupants, some of whom find the rooms uncomfortable. It also makes it difficult for the occupants to converse, unless they are face to face. It can lead to other acoustic defects, both because of the impossibility of distributing the treatment uniformly, and the unevenness of the absorption characteristics of practical materials. However, the general reactions from the users have been that these were the kind of rooms that they needed in order to carry out the necessary quality judgements. Attempts to return to more reverberant control rooms have usually been met with complaints and demands for remedial treatment.*

Some acoustic designers began to question this approach and have developed alternatives. A number of these have been based on non-uniform distributions of acoustic treatment. [3, 4] By implication, if nothing else, the reverberation times of these newer designs will be

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* It is this author's personal view that two factors are effective in this matter. The first is that some programme makers may be losing sight of the principle objective of the programme — that is, to sound 'good' in the audience's environment, not in the control room itself. By making programmes that sound 'correct' in a 'dead' acoustic environment, the minimal amount of studio reverberation which they contain will be almost imperceptible to the majority of the audience. It is analogous to making programmes of such wide dynamic range that they cannot be perceived in full except in the low noise levels of a professional-quality listening room. The second factor is a progressive trend towards a very 'dead' sound, the result of using close-microphone techniques and, to some extent, the enforced use of unsuitable source room acoustics.

longer, because only parts of the surfaces are available for acoustic treatment. Further developments have resulted in more attention being paid to controlling reflections rather than simply absorbing them; in particular, the elimination of the earliest reflections from the vicinity of the listener's position.[5, 6, 7]

The underlying principle is that reflected energy that could otherwise reach the listening position shortly after the direct sound is redirected by specially-positioned, acoustically reflecting or diffusing surfaces. Thus, for the critical first few milliseconds at least, the listener should hear nothing but the sound coming directly from the loudspeakers. Apart from making the stereophonic images clearer, it should also make the sound quality within that region essentially independent of the room itself. This should greatly ease the transfer of a programme between different areas, for example, from studio control room to post production or editing suite. It should also help to achieve consistency between different programmes.

A 'dead' acoustic is not an inevitable outcome, because the key factor is the use of reflection and diffusion rather than absorption. Indeed, the acoustic designer should have considerable freedom in the choice of reverberation time, providing a room which is more comfortable to work in. In practice, in reasonable sized rooms, only about the first 20 – 30 ms of reflected sound can be deliberately redirected in this way. One of the anticipated penalties was that the stereo imaging illusion works over a rather narrower range of lateral displacement from the centre position.[8]

3.   EARLY EFFECTS

In the time immediately following its emission from a small source, a sound wave will propagate as if it were in an open space. Each radial vector from the point of emission can be treated somewhat like a light-ray. An entire branch of acoustics has been developed to study such ray-like propagation. At its simplest, each elemental ray may be followed through its interactions with surfaces and objects as they are encountered. Some of these methods follow these hypothetical rays until they vanish into insignificance.

In reality, the accuracy of representation of the interactions becomes inadequate for such extended multiplication and the system becomes more or less chaotic. However, the representation may be sufficiently realistic to be useful for the short term response and for a few interactions. (Some ray-tracing implementations approximate the later behaviour by assuming non-geometric behaviour for higher reflection orders.)

Many workers have studied the human hearing response in the time domain. The 'early' sound can be subdivided into three different time-intervals*. In the time period up to about 5 ms, there is no directional discrimination between the sound travelling along the direct path from source to listener and any reflected sound, provided that their relative levels are reasonable. This 'precedence (Haas) effect' dictates that the apparent direction of the sound is that of the first arrival.[9]

After this first time interval and up to about 50 – 80 milliseconds after the arrival of the direct path from source to listener, the human auditory process can perceive and interpret a detailed pattern of reflection arrival times. Parameters such as apparent source direction and distance are derived from the sound signal. In the region between 5 and about 10 – 20 ms, reflections are capable of causing confusion about the apparent direction of a sound source.

After about 80 ms, at most, the sound energy is integrated. Reflection events are either not perceived individually or appear as discrete echoes, depending on their level relative to the remainder of the sound.

The human perception mechanism is capable of carrying out all of these processes on a continuous pattern of arrivals — it does not need isolated sound events.

For the acoustic designer of sound control rooms, these properties mean that some control of the pattern of reflections reaching the listener is desirable.

4.   THE CONTROL OF EARLY REFLECTIONS

The control of early reflections and the effects on stereophonic imaging applies only to those rooms in which sound is reproduced by two or more loudspeakers. These include sound control rooms, post-processing areas and listening rooms. (In studios, early reflection control is important, to avoid anomalous acoustic effects, but this is usually a matter of artistic judgement by the programme makers and is part of the production control process.)

The extent to which control of the early reflected energy is necessary is not immediately obvious. Much has been written on the audibility of relatively early 'echoes', essentially beginning with Haas in 1951 [9,10]. Most of this is applicable to large performance spaces. Practically all prior work on simulations relates to the

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*   Some of these figures for time limits are subject to significant discussions and continuing re-appraisal amongst experts. The values given here are intended to be illustrative and representative of the broad consensus of opinion. Their exact values are not relevant to the work described in this Report.

audibility of single echoes. In contrast, the problem of the effects on stereophony of a multiplicity of early reflections in a 'real' room is less well reported*. This is inevitable because of the large number of dimensions involved in such investigations: the time and direction of arrival, relative amplitude and frequency response are all important parameters. When multiplied by even a small number of reflections, the investigation problem becomes intractable.

It is quite clear that the threshold of audibility of a single early reflection, which some results suggest may be at a level of about −30 dB (or even −40 dB) relative to the direct sound, is not the appropriate limiting criterion for the satisfactory perception of stereophony in real rooms. Indeed, there is some evidence that the stereophonic illusion is less convincing (or doesn't work at all) in an anechoic room.[8] The levels of early reflections in conventional sound control rooms, treated with acoustic absorption only, are in the range −5 dB to −12 dB for the first 20 ms. Stereophonic listening has been carried out reasonably satisfactorily for many years in such rooms.

For the purposes of this work, a consensus of the available information suggested that a target of −20 dB and 20 ms would be appropriate for the assessment of stereophony. That is, at the listening position, no reflection greater than −20 dB relative to the direct sound would occur in the first 20 ms.

This was not supposed to be a precisely justifiable and objectively supportable criterion. Rather, it represented a goal which would be realistically achievable in reasonable sizes of room. It encompassed much of the available objective information about the disturbance of stereophonic images. It was a convenient, simple rectangle in time and sound level. What is meant acoustically by 'the listening position' is discussed below.

In other applications, time windows of up to $80-100$ ms are used to calculate some quality criteria,[12–15] but these are not related directly to the perception of multi-channel stereophony as commonly implemented in small rooms. Indeed, it is well-known that the common form of two-channel stereophony, using a pair of spaced sound sources, does not work very well if the spacing of the sources is larger than about $4-5$ m.

Most of the published work suggests that the audibility of early reflections diminishes rapidly for levels below about −20 dB, even for isolated reflections.

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*   At the time of writing, a joint project under the Eureka initiative has been studying the problem[11] and has produced some preliminary results.

To control the early sound energy, those surfaces located in positions capable of creating early reflections at the listening position must be designed to avoid causing such reflections.

One anticipated problem arose from the knowledge that the stereophonic illusion did not work so well in an anechoic environment [8] unless the listener was very close to the centre-line between the loudspeakers. If the principle of the control of early reflected energy was to be usable, some investigation of the sensitivity to changes in the listening position was needed. One of the main purposes of the construction of a prototype room was to investigate the severity of this potential disadvantage.

5.   CONTROLLED IMAGE DESIGN

5.1   Basic assumptions

The first assumption was that the control of early reflections would be achieved by re-directing the sound energy, by deliberate reflection, *away* from the main listening position. Neither of the two practical alternatives, absorption or diffusion, can achieve effective overall attenuations of 20 dB. Even at the optimum angle of incidence, an efficient (practical) sound absorber would only attenuate a reflection by about $7-8$ dB. Most significant reflections would be more nearly at glancing angles of incidence, where the attenuation would be less, perhaps only $2-4$ dB. Adding the extra losses due to path-length differences of perhaps 3 dB and at the most 9 dB, gives an effective overall attenuation of between 5 and 17 dB. This is the range in which conventional designs function, using absorption. Measurements of reflected sound levels as high as −4 dB to −6 dB (relative to the direct sound) have frequently been made in rooms considered to be reasonably acceptable for stereophony. Absorption is, in any case, responsible for the over-treatment of rooms, which was the main reason for considering alternatives to the standard basis of the acoustic design.

The use of modern, wide-band diffusing elements[16, 17] is no better at the control of a single reflection than is absorption, although it is not associated with excessive absorption. By definition, diffusers spread the incident sound energy over a wide reflection angle. The proportion which is reflected in the specular direction is still significant — typically only between 4 and 8 dB below the level which would be reflected from a flat surface. The main problem with the use of acoustic diffusers for early reflection control is the larger effective reflecting surface. Essentially, the whole of the diffusing surface would reflect some fraction of the incident energy towards the listening position. The
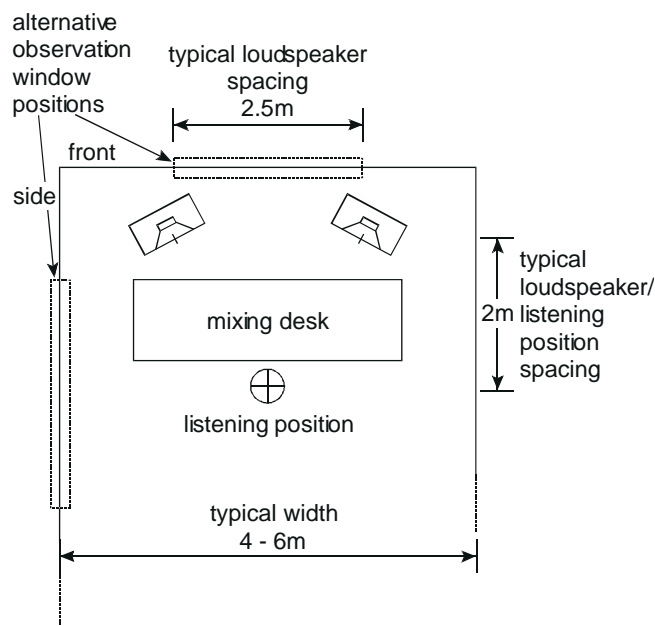
Fig. 1 - Typical control room layout.

result would be a relatively large total energy of diffuse sound.

Fig. 1 shows a plan view of a typical sound control room for two-channel stereophonic monitoring. The principle features are the disposition of the loud-speakers and main listening position as a triangle. In this example, an equilateral trianglular arrangement is shown, but it need not be exactly so. Early reflections to the listening position can occur from either loud-speaker via the front wall or the front parts of the side walls. In elevation, reflections can also occur from the front parts of both ceiling and floor. The rear wall and the rear parts of the side walls, floor and ceiling do not usually cause reflections within the 20 ms time interval to be controlled (in rooms that are reasonably sized).

Any room must have boundaries which together enclose the space in all directions. The essential problem in the control of early reflections is to design boundary surfaces at angles which do not cause early reflections at the listening position whilst, at the same time, enclosing the space. Less generally, in a simple rectangular room some parts of the front and side walls will cause such reflections. The difficulty is to angle those parts without creating new reflections — to make the transition between front and side walls such that no part of the compound surface thus created causes early reflections which pass through the listening position. The same considerations apply also to the transitions between front wall and floor/ceiling.

The second main assumption to be made is the principle of the reflection calculation. It is simple and convenient to consider sound as propagating in straight lines, with specular reflections from any object or surface. In reality, the wavelengths of normal audible sound are significant. Most reflections in rooms are diffraction limited. Thus, the reflected 'ray' has a finite spatial-distribution. The limit at which the cross-section of the reflection may reasonably be considered to be small, for practical purposes, depends on the frequency of the sound energy and the size of the object or surface. The perception of discrete images in stereophony depends mainly on frequency components above about 1 kHz, that is, a wavelength of 0.35 m (although a general impression of spaciousness is conveyed by frequencies rather lower than that). Any object smaller than about 500 mm in diameter (or width) will create reflections which are seriously diffraction-limited — where the reflections could be considered, practically, as omnidirectional. For the reasonable control of reflections at frequencies above 1 kHz the smallest usable object size is, therefore, about 1m. With reflectors of that minimum size, an acoustic design approach based on narrow 'rays' is adequate for stereophony, but has the implied restriction that it will not be valid for low frequencies. Furthermore, any 'reflection free zone' will actually have an unavoidable background level of early reflected sound, resulting from diffraction at edges and discontinuities of objects and surfaces in the room.

For aesthetic reasons, as well as for economy of design and construction, the design principle was based on flat rather than curved surfaces. Curved surfaces would also have an additional problem — that of focusing the low-frequency sound energy.

Again, mainly for aesthetic and economy reasons, the design principle was based on the projection of the three-dimensional reflection processes onto two orthogonal planes — plan and elevation. This significant simplification allowed the use of simple design and drawing aids, avoiding the necessity of working in three-dimensional spaces.

Mainly to allow for the effects of diffraction, the region of early reflection control was designed to be a relatively large volume, rather than a single point. This also simplified the geometric design, and permitted some flexibility in the actual location of the listener. A second listener (for example, a programme producer) could be accommodated within a controlled region.

The control of the stereophonic imaging process by means of reflection involves no acoustic absorption process at all (indeed, it is noted later that the effect worked well in an area with a very long reverberation time). There is, in principle, an entirely free choice for the properties of the later, diffuse sound field. In practice, to provide control of the later energy, the reverberation time must be controlled to a reasonable value. An average reverberation time similar to a

domestic environment was chosen for the initial development work, as a reasonable starting point.

Because the reflection of sound may be thought of as creating virtual images of sources, the name Controlled Image Design was devised. It is similar to, but uses different design principles from, a Reflection Free Zone (RFZ).[5, 6] One of the main differences, in practice, is the use of the design method to accommodate the principle in rooms of rather smaller size than is typical of RFZ rooms. This principle is applicable only in control rooms and listening rooms for small numbers of people. It is not generally appropriate to studios or live performance spaces, mainly because those areas usually require more flexibility in the location of sources and 'receivers' than do control rooms.

5.2 Practical implementations – computer program

The first step in the design process was to specify the listening position. Geometrically, this was trivial. Acoustically, the effects of diffraction would ensure that some energy would be reflected in non-specular directions. Thus, it was necessary to consider a finite zone around the nominal listening position which was large enough to make these effects meet the criterion at all frequencies important to the stereophonic illusion. Accordingly, in each projection, a circle was drawn around the nominal listening position from which all first-reflection sound rays were to be excluded.

The positioning of a single reflecting surface to avoid causing a direct reflection, given fixed source and receiver positions, is also trivial. However, a control room for stereophony involves two sources, each with an entire hemisphere (at least) of directions for potential reflecting surfaces. Given the need to avoid a particular region around the main listening position, there is also a choice for the direction of the reflected sound.

By projecting the design onto the two main sections, plan and elevation, these degrees of freedom were reduced to semicircles and to a binary choice for the direction of the reflection. One small additional cost of this simplification is that the designs for plan and elevation must be coordinated, for aesthetic reasons. The complexity of this problem was such that assistance from a computer was helpful, though not essential.

Initially, a computer program was written which plotted the limiting angles for reflecting surfaces to ensure that the reflected sound passed through one of a number of selected points around the listening position. The points were chosen for different regions of the room

boundaries and source position to be such that the reflected sound 'ray' did not pass nearer than a minimum distance from the main listening position (coincidentally, similar in principle to the methods used for RFZ designs). This was soon found to be too restrictive. The program was modified to use a circle around the main listening position and to generate the limiting angles of surfaces which would just cause the sound rays to be tangential to that circle. The design method also assumed omni-directional radiation patterns for the sources. In practice, some additional attenuation is likely to occur at extreme radiation angles, making it less important that some surfaces are considered as thoroughly as others.

Fig. 2 shows a typical output from the program. The two source positions, the main listening position and the room boundaries are marked. The circle around the main listening position, with a radius in this case of 1.25 m, is also shown. The curved (broken) lines show the locii of the limiting angle for a reflecting surface which would just create a tangent to the circle around the main listening position. For any reflector position in the room there is a choice of which is the more critical source and to which 'side' of the listener should the reflection be directed. The discontinuities in the curves, showing transitions from one source or tangent criterion to the other, are visible.

As discussed above, these curved surfaces were not practical as real surfaces. Instead, the curves were used as guidelines for the design of flat reflecting surfaces which are themselves just tangential to the curves at the most critical point. In this way, reflections from the flat surfaces will either be just tangential to the circle around the listening position or will miss by a greater or lesser amount.
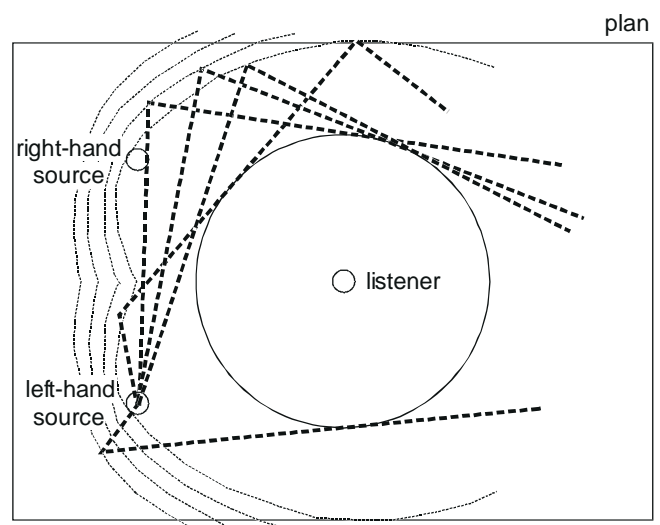

Fig. 2 - Typical output from computer, showing limiting reflector angle guide lines
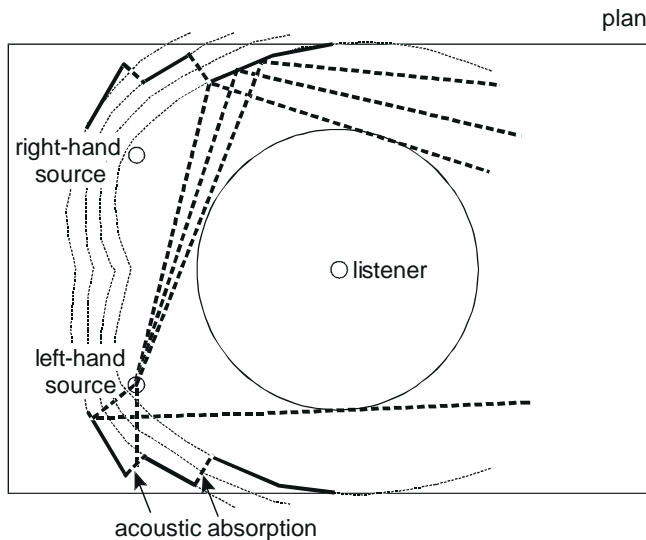
Fig. 3 - Reflecting panels fitted to guide lines.

In most reasonably sized rooms, it is not possible to make the transition from end wall to side wall without introducing step discontinuities (analogous with the steps in an optical Fresnel lens). These discontinuities were to be filled with acoustically absorbing material. Fig. 3 illustrates the principles, again using a small selection of sound rays.

In order to facilitate the design, the computer program which created the limiting curves was able to generate its output in a form suitable for importing into a computer drawing package. This simplified the (interactive) fitting of reflecting surfaces which just satisfied the angle criterion at the worst point.

The above description has been given in terms of the plan. The elevation was treated in the same way, except that it is impractical to shape the floor. It is also difficult to control the reflections in elevation in the same way as for the plan because of the usually much smaller dimensions in the vertical section. For both of these reasons, the design relied on the presence of the mixing desk to control some of the reflections in elevation.

The final consideration was the coordination of plan and elevation designs. It was aesthetically important to ensure that the discontinuities and bands of absorption coincided at their junctions in the two directions. Fig. 4 *(opposite)* shows the complete design sketch for the prototype room, illustrating this coordination. In practice, the elevation design constrains the positions of the reflecting surfaces, with relatively little flexibility in typical sized rooms, so that the design for the plan has to be adapted to fit.

5.3   Other benefits

Given a design principle which encourages the use of hard reflecting surfaces, a number of other advantages

are gained. In the past, such surfaces have been seen as undesirable and their uses were minimised. Windows (especially the main observation window between studio and control room), doors, technical equipment and, more recently, computer trolleys and video monitors, were all tolerated out of necessity. Many of these features can be included as part of the Controlled Image Design. Monitors, clocks, signalling lights and other hardware can be built into glass-faced enclosures. Doors and windows can form parts of the main reflecting surfaces, provided that they are appropriately angled.

Most of the applications of Controlled Image Design described in this report were based on the use of free-standing loudspeakers. This has been the most common arrangement in the BBC, because of lower initial costs and ease of maintenance and replacement. However, it is becoming more common to design rooms with the loudspeakers incorporated into the boundary surfaces. This can be accommodated by the CID principle. In fact, the resulting design is simpler, with fewer discontinuities in the angled surfaces, than for the free-standing case (given the same room size).
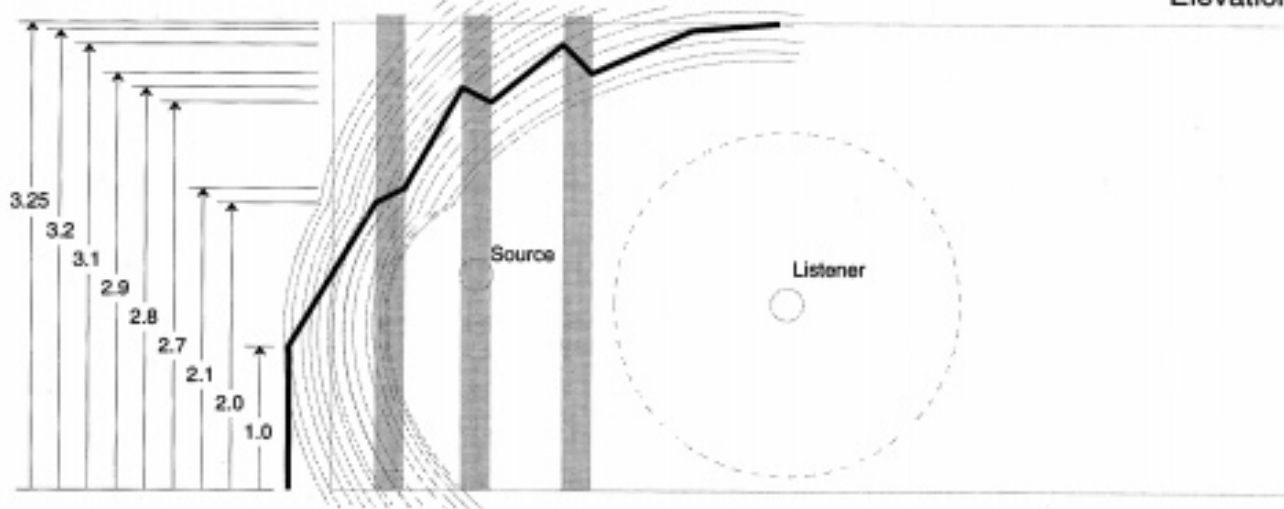
5.4   Very early reflections

One effect of the early reflection pattern which can be particularly disturbing is that of very early reflections from objects near to the line between the source and the listener. This is not usually related to the design of the room boundaries.

Table 1:
Calculated ripple values for different reflection
amplitudes (peak-peak)

relative reflection level dB	p-p ripple dB
−15	3.1
−14	3.5
−13	3.9
−12	4.4
−11	5.0
−10	5.6
−9	6.4
−8	7.3
−7	8.3
−6	9.5
−5	11.0
−4	12.9
−3	15.3
−2	18.8

3.25
3.2
3.1
2.9
2.8
2.7
2.1
2.0
1.0

Source

Listener

Plan

4.9

Right-hand source

Listener

Left-hand source

0.9

0.4

0.2   0.1

0.6
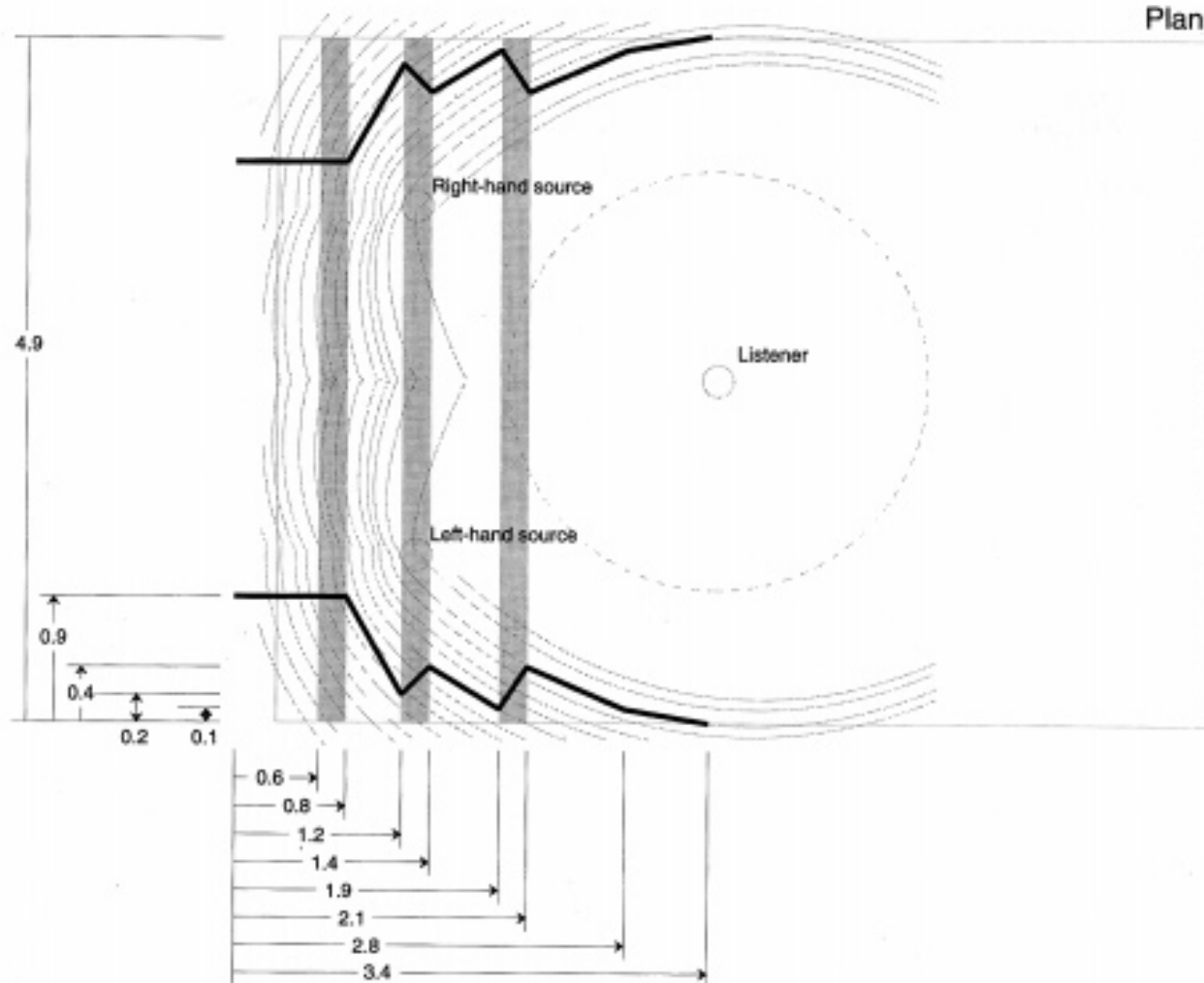0.8
1.2
1.4
1.9
2.1
2.8
3.4

Fig. 4 - Completed design sketch for prototype room (dimensions in meters).
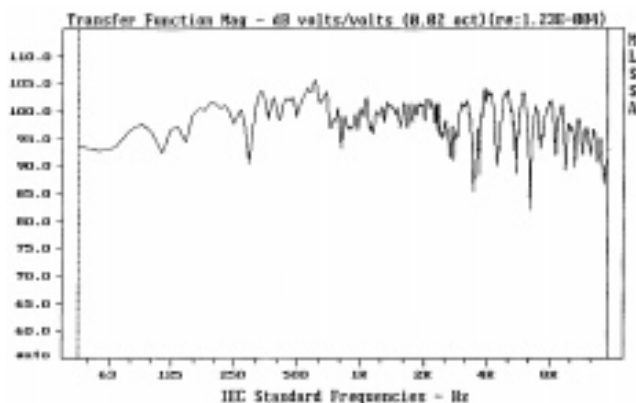
*Fig. 5 - Measured comb-filter response
due to desktop reflection.*

The interaction of two sound waves separated by a very small time difference is not perceptible in the time domain. However, the regular interference pattern which results is detectable as a frequency-domain irregularity. For example, a reflection delayed by 1 ms will introduce a degree of waveform cancellation at 500 Hz and reinforcement at 1000 Hz (and similarly at multiples of these frequencies). This regular distortion of the frequency response, usually called a 'comb-filter' because of its appearance in the frequency domain, is especially disturbing for time delays in the range from 0.5 ms to 1 ms. Most such occurrences are relatively easy to avoid.

Table 1 (*see page 6*) shows the calculated peak-to-peak ripples in the frequency response for a range of relative reflection levels.

The most commonly occurring example of this, in a control room, is a reflection of the sound from the loudspeakers from the top of a studio mixing desk. To avoid it requires careful design of the desk and the layout of the control room, particularly in elevation. The effect is only serious if the amplitude of the reflection is comparable with the direct sound; a reflection at least 9-10 dB below the direct sound, giving a frequency-domain ripple of less then 6 dB, is likely to be innocuous.

Fig. 5 shows a measured frequency response from a control room with a severe desktop reflection. The relative time delay was about 1.1 ms. The regular and severe ripples in the response at frequencies above 2 kHz are obvious.

Appendix I contains an extended discussion of reflections from the mixing desktop surface and the effects of diffraction over the desk upstand.

5.5 Low-frequency response

The use of hard surfaces to control early reflections and the stereophonic image quality has no direct influence on the low-frequency behaviour of the room. This is because the wavelengths of such frequencies are so long that the propagation is affected only by large-sized details. Secondary effects, caused by the modification of the overall room dimensions, may be significant. The effects of room shape and size are discussed in Refs. 18, 19, 20 and 21.

The reduction in overall acoustic absorption may enhance the effects of low-frequency room modes. However, with the decrease in the required total area of absorption, more boundary surface is available for the installation of low-frequency acoustic treatment and the control of the bass reverberation time. It would also be possible to design the high frequency reflectors to be, simultaneously, low frequency absorbers, thus adding to the potential for control of the low frequencies.

With a free-standing loudspeaker arrangement, the reflecting surfaces, if not low-frequency absorbers, will cause a low-frequency comb filter effect because of the low-frequency image formed by some of the surfaces. This was a problem in the first installations using the Controlled Image Design principle and is discussed again later.

6. PROTOTYPE ROOM

6. 1 Prototype room – construction

The room available for use as a prototype Controlled Image Design control room had overall internal dimensions of 6.7 × 4.9 × 3.25 m. This was very similar to the gross size of typical studio control rooms (in fact, the room had originally been constructed as an enclosure for modelling control rooms at approximately full-scale).

The Controlled Image acoustic design was based on a loudspeaker/listener triangle which was equilateral and of side length 2.5 m. The design also incorporated an (hypothetical) observation window in front of the desk operator, that is, between the two loudspeakers.

Fig. 4 shows the complete design for the reflection control. In order to accommodate the design in the 4.9 m width of the room, three step discontinuities were necessary.

In rooms of this size, the first uncontrolled reflection is from the rear wall and occurred in this case at about 19 ms (depending on the listener's head position). Thus, it marginally breached the original design target of 20 ms. The acoustic treatment of this wall had to be such that the reflection was attenuated and diffused. However, the path length difference alone produced about 10 dB attenuation. In consequence, it was not

necessary to install large quantities of absorption on the back wall. Nor was it necessary to use elaborate means for diffusion — scattered patches of normal acoustic treatment generally provide adequate diffusion (and in three dimensions). Parts of the room surfaces not directly used for the reflection control system were used for the distributed acoustic absorption, which controlled the longer-term acoustic sound field (from about 20 ms into the reverberation period). For a mean reverberation time of about 0.35 s, the total area of acoustic treatment used in the experimental room was approximately one quarter of that which would have been used in a conventional BBC design.

The construction of the reflecting surfaces was based on simple timber-framed, plasterboard panels. The steps between the reflecting panels had front surfaces made of 100 mm mineral wool with fabric coverings. The triangular-section airspaces behind the absorbent fronts were untreated and, in parts, of considerable depth. They consequently provided efficient absorption down to quite low frequencies. A small amount of additional low-frequency absorption was provided by the plasterboard panels.

The first results from this room were very promising, even without any additional acoustic treatment in the rear part of the room — with a reverberation time of about 1 s. After the installation of enough acoustic treatment to reduce the overall reverberation time to about 0.5 s, the room was demonstrated to and assessed by groups of broadcasters, architects and managers. The reactions were generally favourable, sufficiently so to encourage further tests and developments. One question was raised concerning the preferred value of overall reverberation time. At about 0.5 s it was long enough to affect the perceived sound quality (although arguably still representative of the listener's environment). There was considerable interest in the aesthetic implications of the new design. In addition, by saving large amounts of acoustic treatment, it was thought likely that such designs could be comparable in cost with those based on absorption alone.

Fig. 6 shows the completed test room, eventually assessed by groups of professional studio managers. Their main objective was to consider the use of the design principles for a major refurbishment project then being planned.

Fig. 6 - Photograph of completed prototype room.

Elevation

3.25
3.2
3.0
2.5
2.2

Source

Listener

Plan

4.9

1.6
1.2
0.50.4
0.2

Right-hand source

Listener

Left-hand source
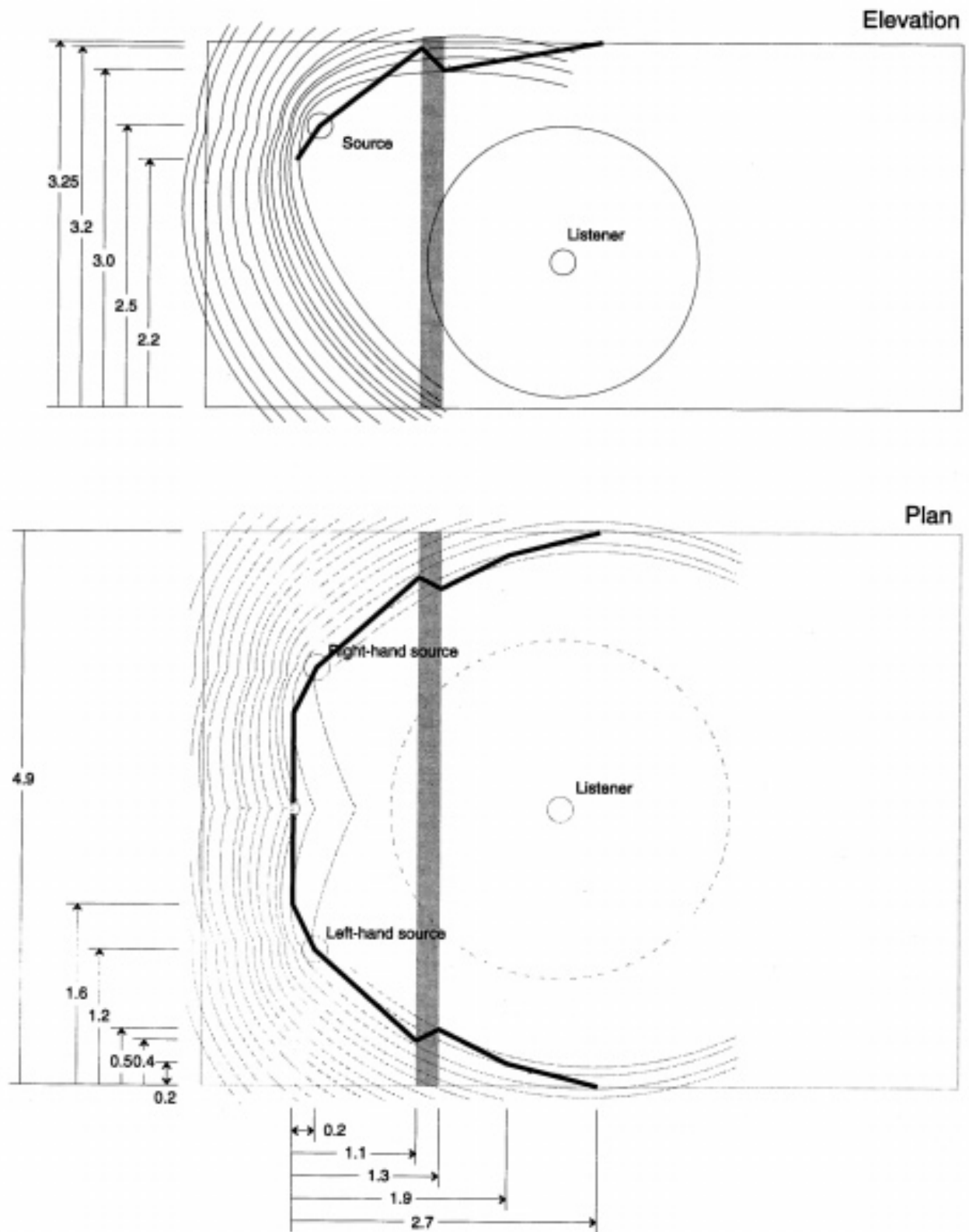
0.2
1.1
1.3
1.8
2.7

Fig. 7 - Unfinished sketch for prototype room design using built-in loudspeakers (dimensions in meters).

This experimental design was based on the normal BBC practice using free-standing loud-speakers. It could just as easily have accommodated loudspeakers built into the front wall, in the fashion then favoured in many other organisations. Fig. 7 shows an unfinished sketch for such a design in the prototype room. After allowing for the rearward projection of the loudspeaker cabinets, the nett effect of the 'building-in' was mostly to bring forward the wall surfaces. In comparison with the use of free-standing loudspeakers, the space in the room occupied by the reflection control system was actually increased, despite the fact that the loudspeakers themselves were located closer to the structural end wall.

6.2 Prototype room – objective evaluation

The measurement of acoustic reflections is a problem with many independent factors. The individual reflections have direction and time of arrival. They also have sound levels which are functions of frequency. For the purposes of this work, it was assumed that the direction of arrival was not important, though in other fields it is known to be so [13, 14, 15]. Thus, three fundamental dimensions remain — time of arrival, sound level and frequency.

Using Short Term Fourier Transforms (STFT) of the measured impulse response, some estimates of the 3-dimensional responses of rooms can be made. The resolutions are inevitably limited by the fundamental restrictions on time-frequency measurements. But, by accepting these and making some simple assumptions (mainly that the frequency responses of reflections are fairly uniform), it is possible to obtain meaningful estimates for the higher frequencies. This enables isolated individual reflections to be identified. Appendix II gives a more comprehensive discussion of the inherent limitations of such measurements. Ref. 22 contains further detailed discussions and presents the results of some experimental verification of the measurement limits. (New mathematical techniques, such as Wavelet Transforms,[23] may make further optimisation of the results presentation possible.)

The results presented in this Report are in one of two forms. The three-dimensional presentations show the room responses as the acoustic amplitude as a function of time and frequency. These responses are the result of frequency-domain smoothing by an approximately $\frac{1}{3}$-octave wide filter. The frequency resolution is, therefore, of the order of $\frac{1}{3}$-octave. Time-domain smoothing results from the length of the weighting window applied to the data before computing the Fourier Transform. The time resolution is of the order of 2 ms. In most cases, the lower threshold of the display has been set at −16 dB relative to the direct sound. This is necessary to remove the clutter caused by the residual diffracted sound energy, which otherwise greatly confuses the display.

The second type of presentation is in the form of 'Energy-Time Curves'.[3]* Although not strictly 'energy', the displays do show the occurrence of delayed reflection responses. In this case, the effective bandwidth is virtually the whole frequency range — the results are effectively averaged over the whole spectrum. This reduces the apparent amplitude of features with relatively narrow bandwidths.[22]

In some of the following presentations of results, the direct frequency response of the loudspeakers themselves has been removed (by computation). This was mainly because the measurements were made over a significant period of time, in different localities and, in some cases, with different loudspeaker types. This equalisation has led to slight artifacts in the responses presented here — namely, an apparent resonance at the upper end of the frequency range. This slight emphasis of frequencies between about 9 – 10 kHz should be ignored. It is not important to the main argument.

Fig. 8 *(overleaf)* shows the Energy-Time-Frequency (ETF) results of a measure-ment for a conventional BBC control room, considered to be typical of that type of design. Reflections are clearly visible from equipment trolleys (≈2 ms), ceiling (3 – 4 ms), side walls (4 – 6 ms), rear wall (≈12 ms), etc., despite the use of nearly 100% coverage of very effective acoustic treatment. Calculations based on level differences (including corrections for additional path length) suggest an effective absorption coefficient of around 0.6 – 0.7. In all of these cases the angles of incidence of the sound on the acoustic treatment were close to glancing angles.

Fig. 9 *(overleaf)* shows the results of an identical measurement for the prototype Controlled Image Design room. A small group of 'defects' are evident between about 9 and 12 ms. Their amplitudes were about −14 dB relative to the direct sound. Investigation revealed that they were due to corner reflections from the sides of the first set of modular acoustic treatment on the ceiling and side walls respectively. (This treatment was in the form of 180 mm deep, 600 mm square boxes, and occurred because of the prototype nature of the room and the internal finishes being incomplete. It was a simple matter to fill these small corners with acoustically absorbing material.) There are also some effects at lower frequencies. These were probably indicating the failure of the reflecting structure to act geometrically at frequencies of the

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*   The term 'Energy' will be used throughout the remainder of this Report, despite the fact that it can be shown to be theoretically incorrect [24]. This usage conforms to the commonly accepted practice.
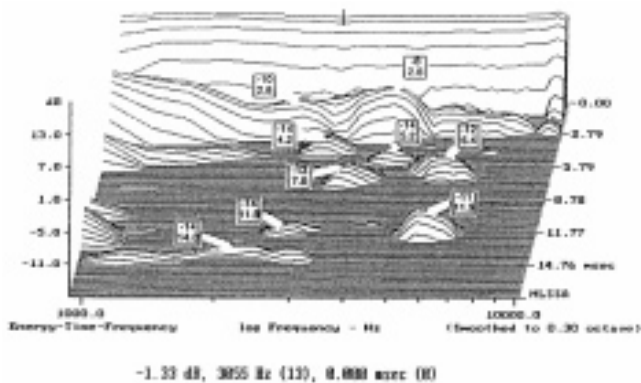
Fig. 8 - Energy-Time-Frequency response in conventional BBC design control room.
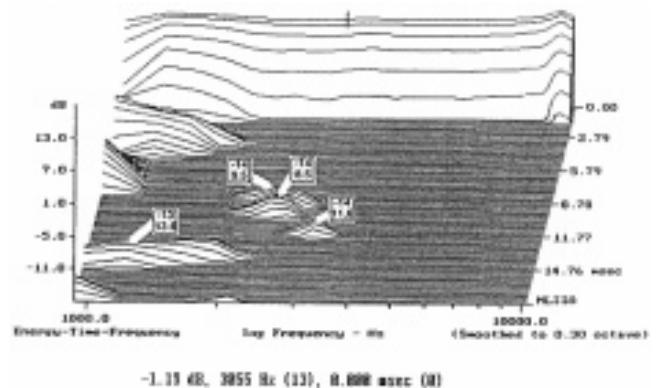

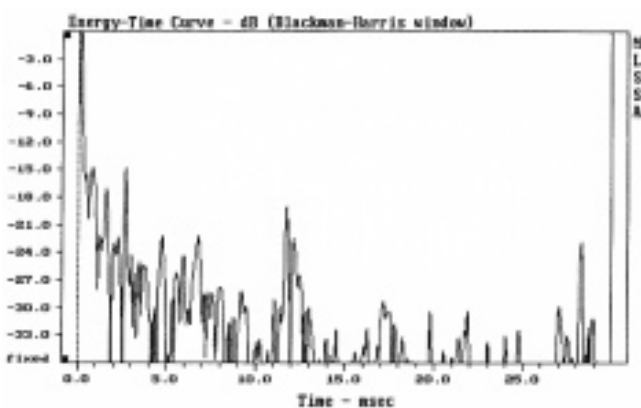*Fig. 9 - Energy-Time-Frequency response in prototype Controlled Image Design room.*

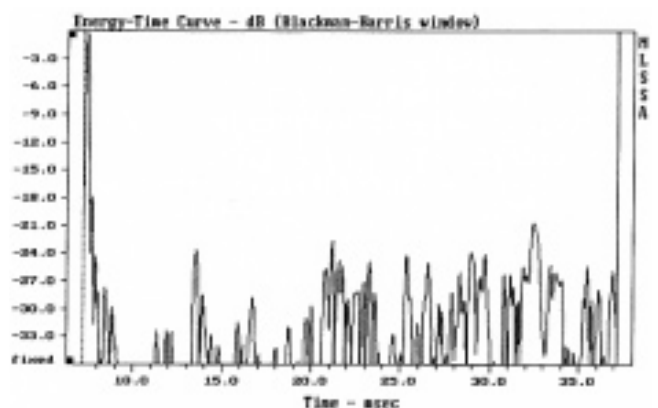*Fig. 10 - Energy-Time response of conventional control room.*

Fig. 11 - Energy-Time response of prototype Controlled Image Design room.

order of 1 kHz and show the residual diffraction limit of these surfaces.

Figs. 10 and 11 show the Energy-Time curves (ET) for the same two rooms. The control of wideband reflection levels to below −20 dB in the test room is evident. In contrast, on the same basis, reflection levels in the conventional room reach −14 dB*.

6.3 Prototype room – subjective evaluation

Subjectively, the prototype Controlled Image Design room showed moderately clear stereophonic images, even before the remainder of the acoustic treatment had been installed. With a reverberation time of over 1 s, the room was clearly very reverberant and unacceptable for use as a control room, but the stereophonic images were well-defined. This was so unexpected that a brief listening test was carried out in a similar environment without the early-reflection control. This was felt necessary because there was no significant experience with listening in small rooms of

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* It should be noted that the time axis in Fig. 11 is shifted by about 8.8 ms. This was due to the different behaviours of versions of the measurement software. In later versions, the inherent propagation delay, in this case 7.8 ms, could not be removed from the display.

such long reverberation time. It was thought possible (though unlikely) that all such rooms could give good stereophonic images! Inevitably, the stereophonic image quality in that room was unacceptable.

The prototype room was treated to reduce the reverberation time to 0.45 s, using conventional acoustic absorption materials (mainly modular absorbers [25]). Extensive listening tests were carried out in that condition. The indications were that the room was generally acceptable as a potential control room and that the stereophonic image quality *at the main listening position* was excellent. The images were sharp, without the apparent elevation which sometimes occurs. They were felt by some listeners to be somewhat 'distant'. At positions away from the main listening position, the image quality was poor, especially for displacements sideways that were greater than about 300 – 400 mm.

At positions well away from the main listening position, the reproduction quality was thought to be fairly poor, but probably no worse than in conventional rooms. Along the central axis of the room, that is, directly behind the main listening position, the

stereophonic image quality was thought to remain good, even outside the nominal controlled reflection region.

A number of these points will be discussed further, in the section relating to the results from the first installations of the Controlled Image Design.

6.4 Consequences of prototype trial

At that time, consideration was being given to a major refurbishment of five studios and control rooms in Broadcasting House, London.

Demonstrations of the prototype room were given to the project team and a number of senior managers. Listening tests were carried out by a total of 11 studio managers and a questionnaire completed. Two different reverberation times, 0.45 s and 0.35 s, were tested. The reactions of these studio managers was generally very favourable, with a preference for the shorter reverberation time. The decision was made to proceed with the Controlled Image Design for three of the new control rooms, B12, B13 and B14.

Appendix III gives the results from a questionnaire completed by the 11 subjects. For a reverberation time of 0.35 s the room scored 81% of the ideal, for a wide range of subjective parameters. The overall score for the 0.45 s reverberation time was 75%.

At about the same time, interest was expressed from a project to relocate a BBC Transcription Service editing facility. That project team also considered the design method and carried out their own listening tests in the prototype room. They also chose to use the new design for the main editing suite.

7.   REAL IMPLEMENTATIONS

7.1 Project Baseband

7.1.1   Controlled Image Design

The BBC's Baseband Project involved the refurbishment of Studios B12, B13, B14, B15 and B16 and their control rooms in Broadcasting House, London. Because of time and financial limitations, B15 and B16 were refurbished to a conventional design. A decision was taken to use the Controlled Image Design (CID) principles for the three remaining areas.

B12 control room was relatively long and narrow, 4.7 m wide by 9.1 m long. The free height, inside the roof slab, was about 3.1 m. The observation window to the studio was to be to the left side of the main listening position at the mixing desk. A window of 1.67 m width

was accommodated by providing a relatively wide reflecting surface at the appropriate location. (The window width was, in any case, limited by structural columns.) The length of the room meant that no significant early reflections from the rear wall were expected. To fit the design into the width and height meant using three sets of angled reflectors. Fig. 12 *(overleaf)* shows the design sketch for the reflecting panels, as supplied to the architectural team. It was anticipated that the programme Producer's Position would be behind (in line with) the main listening position (see Section 8).

B13 and B14 control rooms were designed to be mirror-images of each other, so that only one master design was needed for the reflecting surfaces. In that case, the rooms were rather wide and short with observation windows in front of the main listening position. The width meant that there were no difficulties in incorporating the design for the plan. In fact, an additional observation window was provided, to give the Producer a better view into the studio. The Producer's position, to the side of the main listening position, meant that the stereophonic image quality would, however, inevitably be poor. The shortness of the room meant that a 15 ms reflection control target was only just feasible. The rear wall was, therefore, made as absorbent as possible in the critical reflection areas.

All of the CID rooms were acoustically treated using conventional modular absorbers, to a design reverberation time of 0.35 – 0.4s*. To maintain the high-frequency reverberation time rather longer than had been usual, it was not possible to include a standard acoustic-tile ceiling (which alone is usually responsible for a large amount of high-frequency absorption and very short reverberation times in conventional designs). The visual ceiling for the rear part of the rooms was formed of stretched fabric (with a thin layer of plastic sheet to prevent staining by air currents).

The design presented a challenge for the interior designers and other specialists. The acoustic and aesthetic requirements had to be coordinated with the other requirements, such as the structure, ventilation, visual surface finishes and technical equipment layout.

7.1.2   Project Baseband – evaluation

Figs. 13 and 14 *(see page 15)* show the general appearance of the installations.

Measurements were carried out in all three rooms on completion of the installations. These immediately showed that the loudspeakers had been positioned

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*   The overall acoustic design was carried out by A.R. Woolf, then of BBC Radio Projects Department.
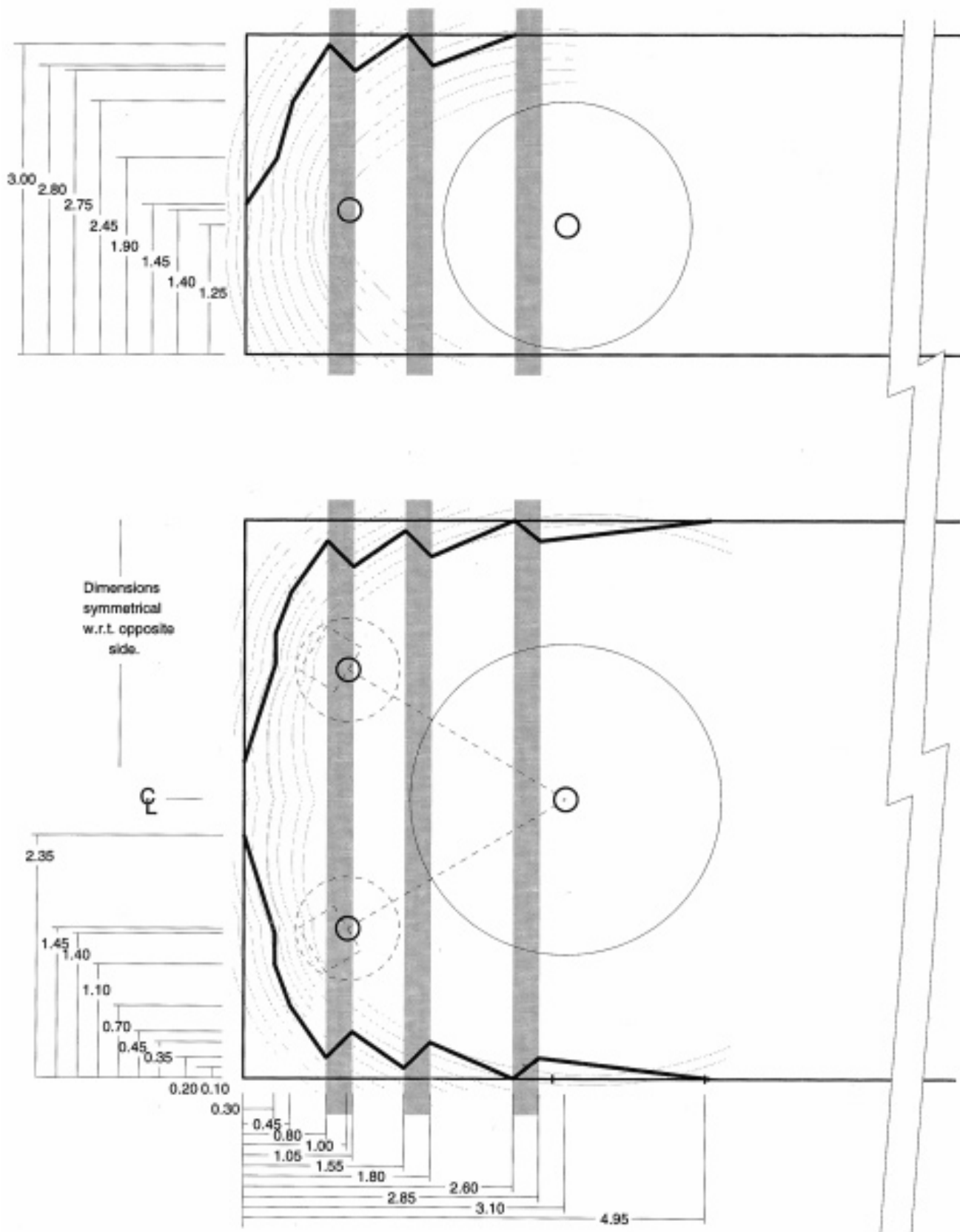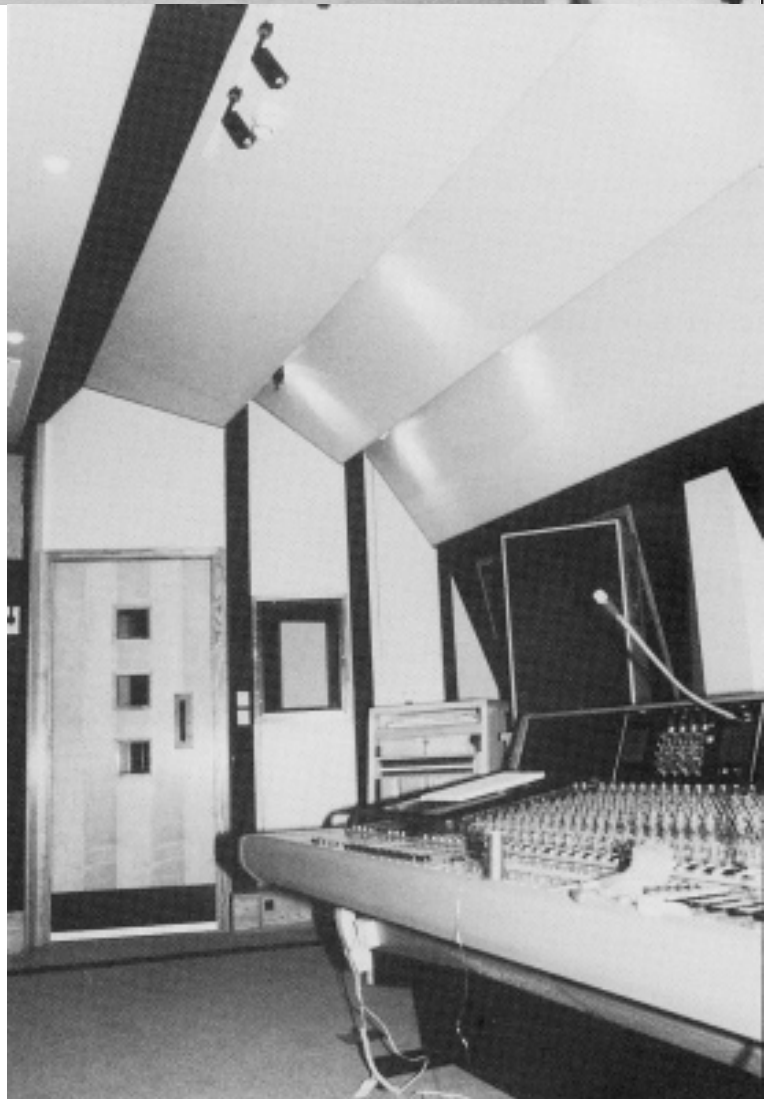
Fig. 12 - Design sketch showing outline plans for B12, CID room (dimensions in meters).

Fig. 13 - Photograph showing B12 CID control room.

Fig. 14 - Photograph of B13 CID control room showing reflecting panels.

about 240 mm higher than the design specified, causing direct, geometric reflections from the tops of the mixing desks in two rooms and nearly direct reflections in the third room. This error was of great significance and is a potential problem in any monitoring area, whatever the basis of the design.

Fig. 15 shows the ET response for the right-hand loudspeaker in B12. Three main features are evident. The first is a reflection at about 1.2 ms/–13 dB. This was the near-direct desktop reflection, the amplitude being controlled by diffraction over the top of the desk upstand. The second main feature, at 7 ms/–15 dB, was a second-order reflection via the top of the desk upstand and a room ceiling panel. This was quite surprising because the upstand top surface was only about 120 mm wide and angled so as not to cause a first-order reflection at the listening position. The third main feature is the group of reflections beginning at about 12 ms. This was caused by the large quantity of furniture and equipment in the room, the installation of which had not been completed.

Fig. 16 shows the ETF response for the same measurement. The second-order reflection feature at 7 ms is clearly visible and, as would be expected from the mechanism involved, is strongly frequency dependent. It had a maximum value of about –8 dB relative to the mean value of the direct sound. The later reflections are also clearly evident and also are strongly frequency dependent.

The most striking feature of Fig. 16 is, however, the unevenness of the 'direct' sound. This was a result of the interference between the direct sound and the desktop reflection. The path length difference of 1.2 ms is not resolved in the time-domain. It corresponded to cancellation at 420 Hz and all odd multiples. This is clearly consistent with the results of the measurement. The shape of the early response also shows severe irregularities on the 'shoulder', that is, at about 2 ms (although the time-resolution of the response is barely able to distinguish such early features). All of these early features are related to the reflection from the main working surface of the desk.

Figs. 17 and 18 show the same kind of responses for B13, left-hand loudspeaker. In this case, there was a direct, geometrical reflection from the top surface of the mixing desk. In the ET response, Fig. 17, this shows at 1 ms/–7 dB. The remainder of the response, up to about 14 ms, is relatively free from significant reflections. The room size was such that the target of 15 ms could not quite be achieved because of reflections from the rear wall. These are shown in the ET response at levels of –16 dB or less, beginning at about 14 ms relative to the direct sound.

Fig. 18 shows the same data, presented as an ETF response. The severe irregularity of the 'direct' sound, up to about 2 ms, is clearly evident. The remaining interval, up to about 14 ms, is essentially free of all reflected energy down to the floor level of –16 dB. After 14 ms, the rear-wall reflections reach a maximum amplitude of about –10 dB relative to the direct sound at some frequencies.

7.1.3 Baseband – results from the second series of measurements

After the measurements described in Section 6.1.2 had been carried out, the loudspeakers in all of the areas were lowered, by 240 mm, to the correct design height. Figs. 19, 20, 21 and 22 *(for Figs. 21 and 22 see page 18)* show the results obtained, after the remedial work, for the same conditions as described for Figs. 15, 16, 17 and 18.

Figs. 19 and 20 show the responses for B12. In comparison with Figs. 15 and 16, the desktop reflection has been essentially eliminated, resulting in a more uniform direct sound response. The anomalous reflection at 7 ms has also been eliminated. All of the other reflections, in the range from 12 ms upwards have been dramatically reduced, to the point where they are all (with one exception) at or below –20 dB. The one exception is at a time delay of 28 ms — well outside the intended control range. The ETF response, Fig. 20, also shows significant improvement, with some reflections at 4-6 ms just rising above the –16 dB floor of the plotted response. Another group of relatively narrowband reflections occurs at 12-16 ms, at maximum levels about –12 dB relative to the direct sound. These are unlikely to be audible. The severe irregularity of the direct sound has also been virtually eliminated.

Figs. 21 and 22 show the repeat results for B13. They should be compared with Figs. 17 and 18. The overall improvements are similar to those for B12, although the room geometry did not allow quite such good control of the desktop reflection. Although no longer a direct geometrical reflection, it is limited by diffraction to about –14 dB relative to the direct sound. The ETF response also shows slightly more irregularity of the direct sound than in B12.

These measurements showed that the acoustic objectives had been largely achieved in all of the rooms. Listening tests indicated that the stereophonic image quality at the main listening position was excellent. The design reverberation time of 0.35 – 0.4 s had been achieved and, as a consequence, the rooms were subjectively less oppressive. The levels of
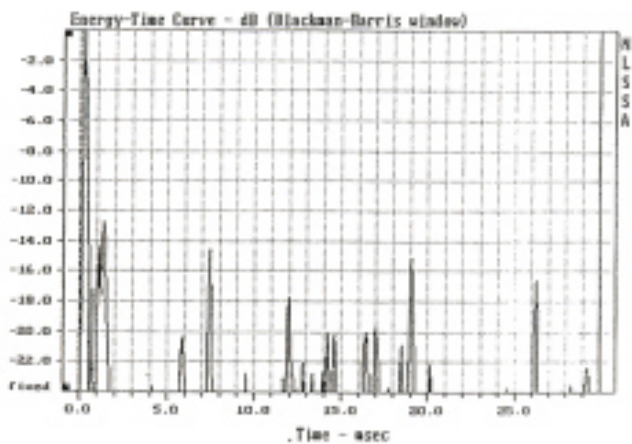
Fig. 15 - Energy-Time response, B12 right-hand loudspeaker with desktop reflection.
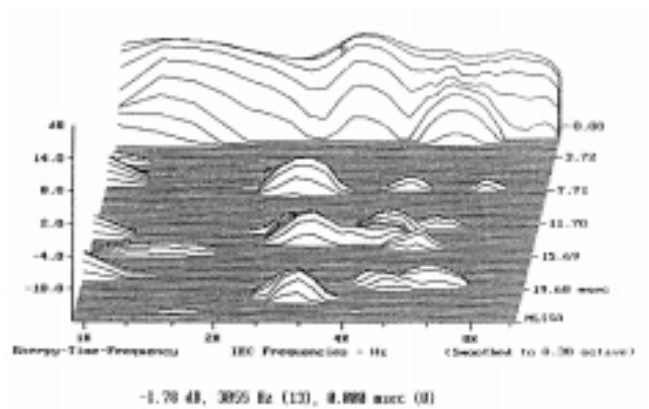

Fig. 16 - Energy-Time-Frequency response, B12 right-hand loudspeaker with desktop reflection.
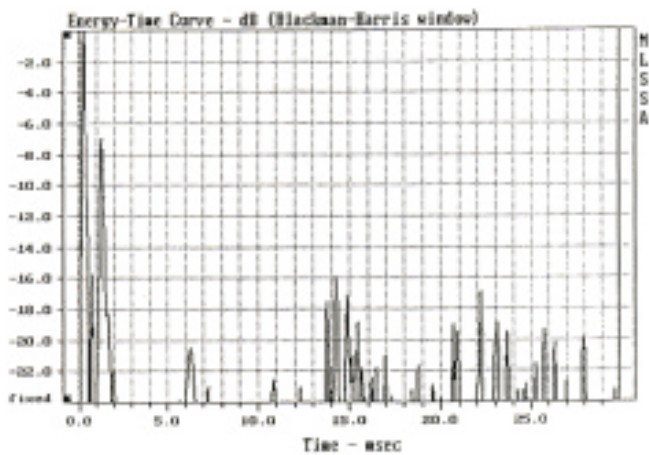

Fig. 17 - Energy-Time response, B13 left-hand loudspeaker with desktop reflection.
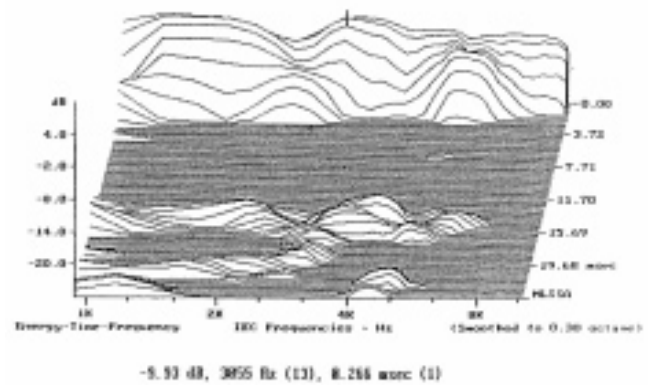

Fig. 18 - Energy-Time-Frequency response, B13 left-hand loudspeaker with desktop reflection.
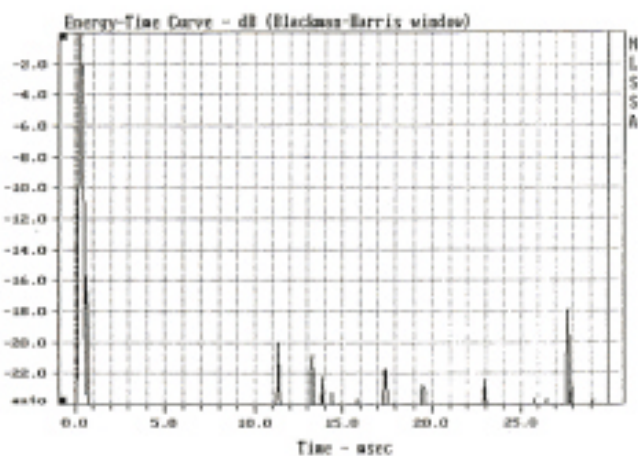

Fig. 19 - Energy-Time response, B12 right-hand loudspeaker after change to loudspeaker height.
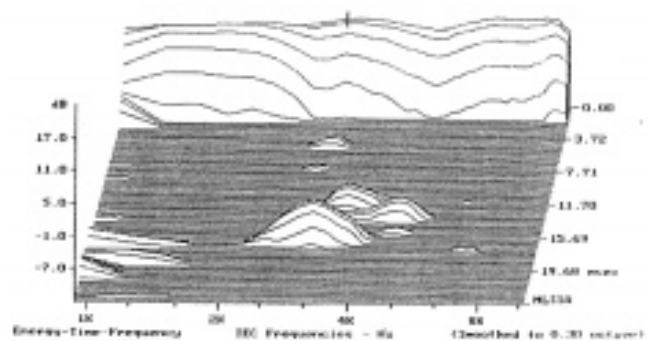

Fig. 20 - Energy-Time-Frequency response, B12 right-hand loudspeaker after change to loudspeaker height.

Fig. 21 - Energy-Time response, B13 left-hand loudspeaker after change to loudspeaker height.

Fig. 22 - Energy-Time-Frequency response, B13 right-hand loudspeaker after change to loudspeaker height.
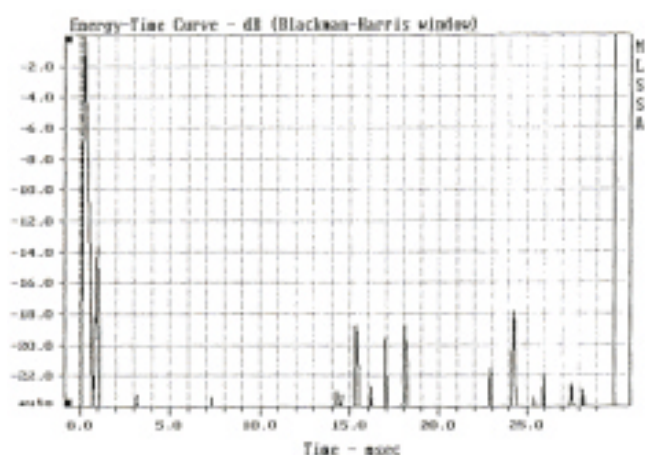
early reflection achieved were similar to or lower than those obtained in conventional control rooms, for reverberation times between twice and three times as long.

The reactions of the programme makers and the subsequent discussions and alterations are discussed in Section 9.

7.2 Transcription Service multi-track, post-production suite

The relocation of BBC Transcription Service to completely new facilities in Bush House gave an opportunity to implement a new acoustic design. As in the case of the Baseband Project, a number of studio managers carried out listening tests in the prototype CID room.

After some discussion and re-testing with different loudspeakers, the decision was made to use the CID principles for the main editing and post-production suite.

In this case, the requirement was for built-in loudspeakers. The gross room dimensions were 6.15 × 5.06 × 3.275 m. Fig. 23 shows the design sketch supplied to the project architectural team. As well as the built-in loudspeakers, several large computer display screens were incorporated into the reflection control structures. The overall design was much simpler, because of the greater room width and the built-in loudspeakers.

Fig. 24 *(see page 20)* shows an ET response measured in the completed room. Fig. 25 *(see page 20)* shows an EFT plot of the same measurement. In this case, the reflection amplitudes were much less than in the Baseband case, mostly because of the additional space and the lack of technical equipment above 'seated' ear
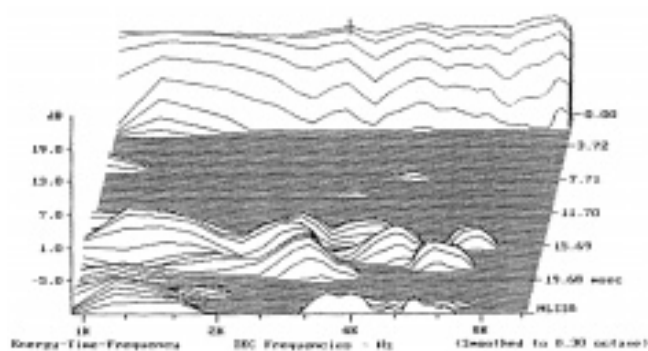
height. In both of these results the range of levels displayed has been increased, otherwise the plots would have shown very little information. In the case of the ET response, the range extends down to −36 dB (instead of −24 dB). For the EFT response, the floor was shifted to −20 dB (instead of −16 dB). The users of the room expressed complete satisfaction with the final acoustics.

7.3 Other proposals

At the time of writing, several outline sketches for new or refurbished areas have been prepared, but no more projects incorporating CID principles have been started.

One project which is progressing, which is being designed by an external consultant, appears to incorporate the same principles.

8. USER REACTIONS TO PROJECT BASEBAND AREAS

Significant problems have been encountered in the Baseband CID areas, particularly in B12. All of the following comments and investigations relate specifically to B12, although many of the problems have been reported in B13 and B14, but to a much lesser extent.

When the first measurements were made it was clear that there were some frequency response irregularities at lower frequencies. Fig. 26 *(see page 20)* shows a steady-state response measured in B12. Such responses are always irregular, especially at frequencies below about 300 – 400 Hz in rooms of the usual size for studio control rooms. This is well known.[20, 21] However, in B12 especially, the responses were
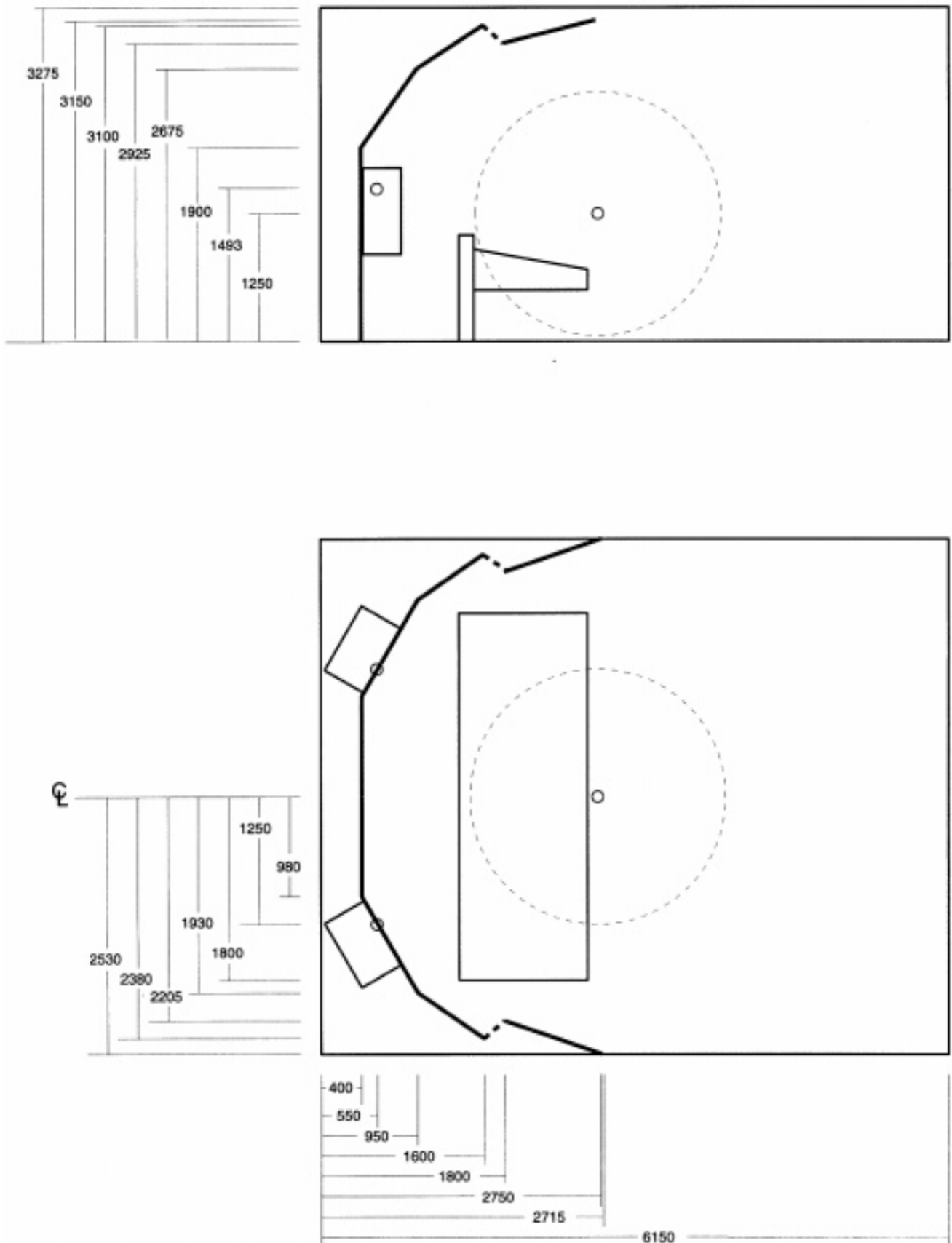
Fig. 23 - Design sketch for Transcription Service post-production control room (dimensions in millimeters).
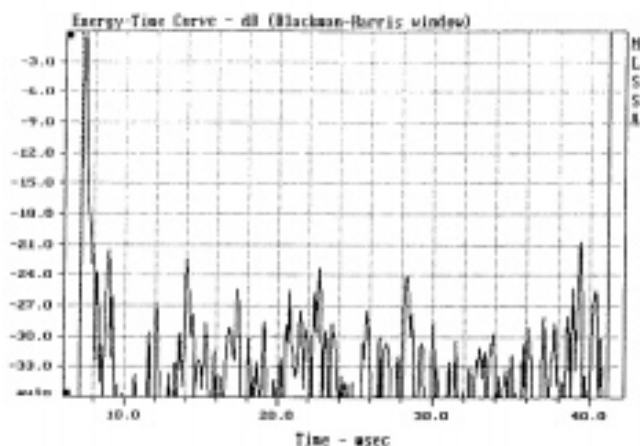
Fig. 24 - Energy-Time response of Transcription Service post-production control room.
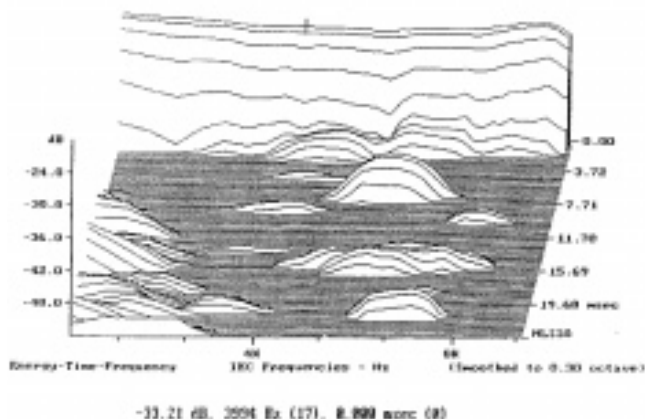

Fig. 25 - Energy-Time-Frequency response of Transcription Service post-production control room.
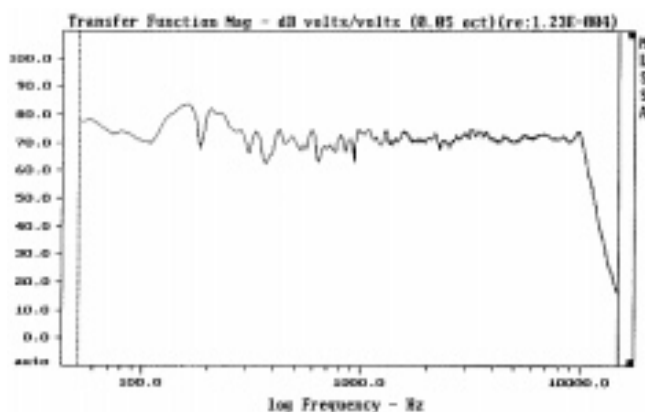

Fig.26 - Steady-state response in B12.

particularly irregular, with a pronounced peak around 200 Hz of about 12 dB.

An investigation was carried out (before the area was handed over to the users). This showed that at least two factors were involved. The type of loudspeaker installed in the room had always shown a particular small irregularity in the frequency response. This usually took the form of an abrupt step in the response, of about 3 – 4 dB at 220 Hz, such that lower frequencies were slightly emphasised. Evidence that the magnitude of this step had increased to about 6 – 7 dB had accumulated over a period of some years. (No definitive information was available because formal measurements on loudspeakers, in a properly-controlled environment, had not been carried for about the preceding eight years.) Measurements on the loud-speakers in B12 showed that they had such a step in the response and that it was at least 6 dB in magnitude.

The second factor was the spacing of the loudspeakers at about 0.75 m from the wall. (The effective low-frequency spacing was not immediately obvious because of the segmented wall structure). This was responsible for a 'comb-filter' effect with a first minimum at 230 Hz. It was estimated that this factor could be responsible for most of the remaining 200 Hz peak.

A third possible factor, which was not considered very much because the first two had accounted for most of the irregularity, was the normal effect of low-frequency room modes. This occurs in all rooms and is usually responsible for most of the low-frequency irregularities observed.[20, 21]

Either of the two low-frequency factors alone would probably have been acceptable — many control rooms were in use with that type of loudspeaker (approximately 500 pairs of which were in service in the BBC at the time). The combination was clearly excessive.

In order to compensate for the peak at 200 Hz, an equaliser network was designed and installed. This provided almost complete correction for both low-frequency factors simultaneously, producing a reasonably level response. Unfortunately, this was inappropriate for two reasons. Firstly, no other room using the same loudspeakers had such a uniform response. In comparison, therefore, the room appeared to be lacking in bass response. Secondly, removing the bass emphasis revealed a particularly unpleasant mid-range coloration or resonance which may have been always present but was less noticeable with the bass emphasis. Whatever the reasons, the subjective sound quality was considered poor. It was agreed that

little progress could be made until the loudspeakers had been changed.

Other problems reported were excessive reverberation and very poor stereophonic images at off-centre positions. In B12, the Producer's position was at the right-hand end of the mixing desk, alongside the operator. This was contrary to the expectations when the room design was discussed. Poor stereophonic images in such positions are inevitable in any kind of room, especially so in a CID room.

There were also complaints about the sound quality near to the rear and down the extreme left-hand side of the room, in positions occupied by tape and other machine operators.

In all of these significantly off-centre positions, the design of the reflecting surfaces was such that a small number of very strong early reflections would be received by a listener there. The amplitudes of such reflections would be of the order of −3 dB at time delays of about 5 – 7 ms.

An investigation of all of these problems was carried out after the loudspeakers had been changed to a different type. With the new loudspeakers, the low-frequency irregularities and the mid-range coloration were no longer the most significant problems.

The first aspect to be investigated was the excessive reverberance. The room certainly sounded reverberant for ordinary conversation, especially near the front. However, with this design it was likely to sound different for sound sources which were not located at the design positions. The reproduced sound from the loudspeakers would, inevitably, sound quite different to other sounds. This discrepancy in the perceived acoustics may have been a source of subjective confusion.

At the main listening position, the sound quality from the new monitoring loudspeakers appeared to be satisfactory. The perceived frequency response and stereophonic imaging were, at the very least, acceptable (much better than in many other control rooms). There was no significant evidence of excessive reverberation. However, at listening positions only 300 – 400 mm from the centre, a curiously reverberant sound was evident. Such positions were well within the region of controlled reflections, a fact which could be demonstrated by measurement. It could not, therefore, have been a result of discrete reflections. After much experimentation, it was discovered that the effect only occurred when both loudspeakers were on and simulating a near-central phantom image. It disappeared when either loudspeaker was switched off!

To overcome the general complaints about excessive liveness, to control the early reflections affecting the Producer's and machine operators' positions (and in an attempt to make the room reasonably acceptable) additional acoustic absorption was added as an experiment. This absorption was in the form of approximately 10 m^2 of 25 mm thick polymer foam. It had high absorption at all frequencies above about 1 kHz. It was installed over the front of the reflecting panels, covering nearly all of the front surface of the room from a height of about 1 m to 2.5 m. The effect on the overall room acoustic was to reduce the average reverberation time from 0.35 s to 0.26 s (still somewhat live in comparison with many control rooms).

Subjectively, most of the problems were reduced. The sound quality and stereophonic imaging at slightly off-centre positions were greatly improved — the excessive reverberation effect being much less noticeable. At more distant listening positions, the quality was improved, though still not good. It is probable that the quality at the more off-centre positions was no worse than in any other kind of design.

At the time of writing, no further user reactions have been received. It has been proposed that additional acoustic treatment will be installed in B12 control room, following the principles of the experimental tests.

9. DISCUSSIONS

The problems encountered in B12 raise the fundamental question as to whether the Controlled Image Design principle actually works in practice. It was certainly well-received as an experimental test in the prototype room. During those extensive tests and demonstrations, no adverse comments were received about the sound quality *at the main listening position*. On the contrary, all comments were favourable. Indeed, there was very little wrong with the perceived sound quality at the main listening position in B12, after the loudspeakers had been changed. With the benefit of hindsight, it is probable that insufficient attention was given to assessing the off-centre sound quality in the prototype room. However, subsequent listening tests in the prototype room showed that the excessive reverberation effect at slightly off-centre positions did occur, but only to a degree which could easily be missed (and was).

The effect disappeared when only one loudspeaker was active. With two spaced loudspeakers, reproducing similar signals, a strong interference pattern is established, resulting in a pronounced comb-filter effect. For small differences in phase (or path-length)

the interference pattern will have a coarse structure and the amplitude variations will be large (perhaps as large as 15 – 20 dB peak-to-peak for a nearly central image). For example, for a lateral displacement from the centre of 400 mm in a typical size of room, the path-length difference would be 390 mm. The interference pattern would repeat at intervals of 880 Hz.

In conventional rooms, this interference pattern is not readily audible; at least, it is never reported as a specific problem. In such rooms, the presence of other early reflections, at relative amplitudes of at least −6 dB, means that the interference pattern due solely to the difference in distances of the loudspeakers is hidden amongst two additional ones for each reflection which is present at a significant level. Most conventional rooms have significant reflections from the ceiling and at least one (usually both) of the side walls. In such a complex mixture of interference patterns, the one due to path length differences from the loudspeakers is quite likely to be unnoticed. In contrast, in a room with no other significant early reflections, the single isolated interference pattern is likely to be perceptible. The subjective effects of such patterns have not, to the author's knowledge, been studied.

In B12, this effect interacted in some way with the fact that the room was relatively long and narrow and with the fact that the front half of it had virtually no acoustic absorption. Rooms which are 'live' at one end and 'dead' at the other have a long history [3, 4] and are not known as being fundamentally defective. Many such rooms have been built throughout the world, with no widely reported problems*. It was this recognised support for the live-end/dead-end design which originally led, in the Controlled Image Design, to placing all of the acoustic absorption at the rear of the room and making the front of the room non-absorbent. There is nothing fundamental about the CID approach which determines this. It is just as feasible to provide smaller reflecting surfaces, but, only at the particular locations where they are required. The remainder of the front part of the room could be treated with acoustic absorption. A slight difficulty might then arise if it was required to maintain a reasonably high value of average room reverberation. Then, the total amount of acoustic treatment required would not be sufficient to treat all of the surfaces to a adequate degree to avoid other acoustic anomalies. However, in most cases this would not be a significant problem.

In B12, the combined subjective effect of the interference pattern, the disposition of the acoustic treatment and the shape of the room was of excessive

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*   It is, of course, possible that problems do occur and are not widely reported because of commercial considerations.

reverberation. That it was not real reverberation could be concluded from the facts that it did not happen with only one loudspeaker active, that it was much reduced by the addition of a relatively small quantity of acoustic treatment and that the apparent length of the reverberation was much greater than any measured room reverberation. The subjective effect was much more like that obtained outdoors from a distant, barely-audible, radio, tuned to the same station as a nearby one. No real mechanism was present in the room to create that physical condition.

The magnitude of the effect must have been a function of B12 itself — a conclusion reinforced by the fact that B13 and B14 were reported to be much less problematical. The only substantial difference between B12 and all of the other CID rooms was the aspect ratio.

The experiences in the Baseband Project represented a significant learning curve — in retrospect, it might have been wiser to try out the design in a single, experimental production area. It is likely that, had the requirements for good listening conditions at the right-hand end of the mixing desk, at the rear of the room and down the extreme left-hand side of the room been properly discussed, B12 would not have been designed to use the CID principles which deliberately biases the 'good' acoustic to the main listening position.

The installation of a Controlled Image Design room in Bush House, for Transcription Service has, in contrast, been entirely satisfactory. In that operation, sound quality at other positions was less important — the room was most often used by one person. Also, that room was rather larger overall and not so long and narrow. Having the loudspeakers built into the wall eliminated the low-frequency wall reflections so that the 'comb-filter' effect was not a problem.

For the future, it seems that reflection control might continue to offer the benefits originally expected, but that its application should be confined to those areas where the important listening position is well-defined. For future designs, until the full effects of the live-end/dead-end syndrome have been quantified, it would seem advisable to distribute the acoustic absorption more uniformly around the room.

10. CONCLUSIONS

The concept of reducing the amplitudes of early reflections in studio control rooms to insignificant levels has been demonstrated to be technically feasible. One of the objectives was to avoid the over-treatment

of rooms and to produce a room which was less oppressive for the occupants.

Based on a simple geometric approach to the design of reflecting surfaces, it has been shown that it is entirely feasible to fit such designs into room sizes typical of studio control rooms.

The computer-assisted design aid developed as part of this work greatly simplified the task of ensuring that all of the geometric acoustic principles were satisfied. However, in reality, the acoustic result is modified by diffraction effects at the lower end of the important stereo frequency range. The initial targets of -20 dB and 20 ms were shown to be not quite achievable in the test room. Even so, the prototype room was considered to be live yet accurate and revealing, with a comfortable environment for the occupants. Some reactions have included comments that it may be 'too analytical'. This may be more an observation on the failings of current designs than a criticism of the Controlled Image Design.

Based on the results from the prototype room and some recently published work, the design targets were relaxed to 15 ms/15 dB.

Four new installations based on the principle of Controlled Image Design have been completed. The first measurements showed that the main objectives of the design, the reduction of all reflected sound energy at the main listening position in the period up to about 15 ms after the arrival of the direct sound to levels below -15 dB relative to the direct sound, had essentially been achieved.

Although the objective targets were achieved, there were subjective problems in some of the Controlled Image Design implementations which required remedial work. These problems also indicated that the use of such designs is only justifiable where the main listening position can be pre-determined. At positions away from the main listening position, the overall sound quality and the stereophonic image quality may unavoidably be poor, perhaps worse than in a room of conventional design.

The provision of wholly-reflecting surfaces at one end of a control room may lead to subjectively excessive reverberance, especially in rooms which are rather long and narrow. Though many satisfactory rooms have been constructed throughout the world using a live-end/dead-end approach, it may be unsatisfactory in combination with complete control of the earliest reflections. The principle of Controlled Image Design can be achieved using hard reflecting surfaces only over the areas important for the control of specific reflections.

The problem of reflections from the mixing desk surface is important, not only for the Controlled Image Design, and is complicated by the effects of diffraction over the top edge of the desk upstand.

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12. ACKNOWLEDGEMENTS

APPENDIX I

Diffraction and desktop reflections

The usual form of construction of a mixing desk (console) incorporates a main working surface which is essentially planar (although some may be subdivided into smaller sections). A rear upstand carries level-monitoring meters and other displays. Although the main surface is broken by control knobs and other irregularities, it remains an effective reflector for sound energy components with frequencies between about 1 kHz and 10 kHz — those frequencies of most importance for stereophony. It is a simple matter to position the desk and loudspeakers such that a direct geometrical reflection to the listening position is avoided. This usually requires the loudspeakers to be placed fairly low down in the room and may rely on the desk upstand to provide a degree of screening. For this purpose, the separate components of a loudspeaker must be considered individually — the individual drive units do not act together to produce a combined response.

However, sound propagation is a wave function subject to diffraction effects. To some extent, the sound wavefronts will be distorted by the desk upstand so that they are deflected downwards towards the main working surface. The geometrical 'shadow' zone will in fact reflect some sound energy towards the listener. Conversely, in the 'non-shadow' zone, the sound energy levels will be less than they would be in the absence of the obstruction (because some of the energy has been deflected in a different direction).

The subject of diffraction is too complicated for treatment here. Some measurements were carried out to determine, in the context of a reflection from the top surface of a mixing desk, the approximate magnitude of the effects. The obstruction was in the form of the edge of a large and thin (15 mm) sheet. For the case of the limiting angle, where the direct sound path just grazes the edge of the obstruction, it was found that diffraction reduced the level of the sound by about 5 dB. This was reasonably independent of frequency over the range 1 kHz – 10 kHz. Thus, for a just geometric reflection the sound energy could be assumed to have an excess attenuation of 5 dB, that is, in addition to the spreading loss and any loss at the actual reflection.

For the case where the obstruction projected into the direct sound path by 100 mm (at a distance of 0.75 m and for a listener-loudspeaker distance of 2.2 m) the attenuation due to diffraction was about 10 dB, although by that stage a moderate function of frequency (that is, −8 dB up to 1 kHz and then falling fairly uniformly to about −14 dB at 10 kHz).

APPENDIX II

The measurement of time-frequency responses

Audio and acoustic systems are usually characterised by parameters which are functions just of frequency. In the real world, systems usually respond to a stimulus which is time-dependent. For example, the output from a microphone is an electrical copy (more or less distorted) of the acoustic sound pressure time function. Both are scalar functions of time. The concepts of frequency response and bandwidth exist only through some form of transform, usually the Fourier Transform in linear systems. However, it is well known that the system time domain function 'impulse response' theoretically contains all of the information necessary to specify a system fully (at least for a time-invariant one).

All of the meaningful interpretations of time domain events in the frequency domain (and indeed, most aspects of analogue circuit theory) are based on the Fourier Transform, which provides a means of translating between the two domains. It can be shown that the original time signal and a summation of the Fourier components are identically equivalent representations. For perfect frequency resolution, the signal must be available to the analysis for all the past and future time for which it exists. Conversely, an infinitesimal time event can carry no frequency information at all. In the real world, such ideal signals cannot exist. It is clearly sufficient to limit the time domain record to some reasonable length, such that the effects of the truncation are acceptable, in the context of the measurement. The product of time and frequency resolutions is a constant, approximately equal to unity.

The human hearing system is a complicated signal processor, especially in the context of the effects employed to create the stereophonic audio illusion. For reflections in a small room, the interval up to about 15 ms is the most important. In the period up to 5 ms reflections are not perceived directly but they can have an important influence on the sound quality because of interference with the direct sound. In most cases of very short delays, a surface would not be large enough to cause a strong reflection at 500 Hz, but it might be at 1500 Hz and higher harmonics. Such cases are frequently encountered in control rooms where, for example, the flat surface of the mixing desk usually forms an efficient reflector. The (potential) reflection from the top surface of the mixing desk is likely to occur at about 0.8 to 1.2 ms after the direct sound from the loudspeakers.

Individual early reflections from room surfaces are likely to occur at about 3 ms (from the ceiling), 7 – 8 ms (from the side walls) and 15 – 20 ms (from the rear wall). Thus, for measurement of the acoustical effects of early reflections in control rooms, it is desirable to be able to resolve time differences of the order of 1 ms. Fortunately, the stereophonic illusion involves mostly the higher frequencies; the main image-forming frequencies are those from about 1 kHz upwards.

These factors lead to measurements based on time resolutions of about 0.5 – 2 ms, resulting in frequency resolutions of the order of to 2 – 0.5 kHz. As a result, it is conceptually possible to identify and measure reflections with time and frequency resolutions high enough to be useful for the investigation of stereophonic systems. There are two particularly useful measures of short-time responses — the so-called 'Energy-Time' response (ET) and the 3-dimensional Energy-Time-Frequency response (ETF). The first of these, the Energy-Time curve, is in fact the magnitude of the complex system impulse response. It is usually taken to represent 'instantaneous energy'. Although its precise theoretical nature is seriously disputed [24], it does present one view of the time domain response in which representations of discrete reflections are easily observed. In the ET results presented in this Report the effective bandwidth of the measurement is approximately 500 Hz to 8 kHz and the plotted value is the average response over that frequency range. The apparent amplitudes of effects occurring in relatively narrow frequency bands are reduced by this frequency-domain averaging. The effective frequency domain weighting is constant for linear frequency, resulting in a strong bias towards the higher frequencies.

The second useful measure of response is the 3-dimensional ETF, or 'waterfall' plot. For this, the start of the Fourier Transform block is progressively shifted in time, to produce a series of frequency responses at different times. The time resolution is limited by the length of the transform window. Despite these

limitations, a useful display indicating approximate times and frequency responses of reflections can be obtained. In the ETF results presented in this paper, the scale has been adjusted to show only the response down to −16 dB relative to the direct sound (20 dB in one case). Also, a frequency-domain smoothing function, corresponding approximately to a one-third octave resolution, has also been applied, to reduce the 'comb filter' interference patterns. This makes the implicit assumption that no features of the response involve effects with a bandwidth narrower than one-third octave.

APPENDIX III

Results from the Listening Tests in the Prototype Room and the Questionnaire

For the formal assessment of the prototype room by studio managers (to determine whether or not the design should be used for the B12 – B14 refurbishments) a questionnaire was completed by each of the 11 subjects. Overall room reverberation times of both 0.35 and 0.45 s were assessed.

Questionnaire returns

| RT, s | Averages | | % |
	0.35	0.45	change
Image sharpness :-			
centre	4.73	4.36	–8
off-centre	2.82	2.45	–13
further back	3.91	3.27	–16
rear of room	3.55	3.00	–15
sides of room	2.45	2.09	–15
Sound stage size :-			
side-side	4.70	4.70	0
front-back	3.29	3.29	0
presence	3.00	2.89	4
volume/loudness	3.00	3.00	0
lateral perspective	4.00	4.00	0
front-back perspective	3.00	3.17	6
coloration	3.62	3.00	–17
reverberation	3.10	2.40	–23
ambience	4.36	4.45	–2
conversation	4.27	4.27	0
aesthetics	4.09	3.82	–7
acoustics	3.91	3.36	–14

The scale ranges were all 1.0 to 5.0. The scale descriptions were:

Scale number	1.0	5.0
Attribute		
Image sharpness	poor	good
Stage size	small	large
Presence	distant	close
Volume/loudness	quiet	loud
Perspective	narrow	wide
Coloration	coloured	neutral
Reverberation	excessive	neutral
Ambience	unpleasant	comfortable
Conversation	difficult	easy
Aesthetics*	not at all	very much
Acoustics*	not at all	very much

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*   The last two items were prefaced by a question 'Ignoring the acoustic/aesthetic aspects, how much would you like to work in a room like this?'. They were intended to obtain overall impressions of the acoustics and aesthetics separately.

Some of the scales (stage size, presence, volume/loudness and perspective) were intended to be centred on neutrality, that is, an ideal room should score 3.0. The remainder were intended to be one-sided scales, with 1.0 indicating a poor quality attribute and 5.0 indicating high quality. In some cases, for example "Sound stage size: side-side" it appears that the subjects' interpretation might have differed from the intention.

The percentage change in the attributes when going from 0.35 s to 0.45 s is also shown.

The results indicate a clear preference for the 0.35 s reverberation time. For that condition, most of the attributes scored close to their ideal values. For the longer reverberation time, the scores were all further from the ideal, except for the small positive difference in the 'front/back perspective'.

The questionnaire was not intended as a strictly formal subjective test. It was intended more to act as an *aide memoir* and note-pad for the subjects. Many of the subjects made no distinctions between the attributes for the two conditions. The differences between the overall averages are dominated by the results from the few subjects who did make the distinction. Nevertheless, the differences are probably real (and are consistent with subsequent events, see Section 8).

Omitting the results for non-central image quality (which was expected to be poor, is poor in any other room and was not a factor in the design) and assuming that the subjects took the stage width attribute to be best for the maximum width (which was not the intention but was, fairly clearly, the subjects' understanding), the overall achieved scores were 81% for 0.35 s reverberation time and 75% for 0.45 s. This overall score was the average value of all attributes, normalised to their optimum values.

For scores with an optimum value of 5.0 the normalised value was given by

$$\text{Normalised attribute} = (\text{score} - 1) / 4.$$

For scores with an optimum value of 3.0, it was

$$\text{Normalised attribute} = 1 - \sqrt{((\text{score} - 3) / 2)^2}, \text{ expressed as percentages}$$